Research report

# Sub-second "temporal attention" modulates alpha rhythms. A high-resolution EEG study

Claudio Babiloni[a,b,c,*], Carlo Miniussi[b], Fabio Babiloni[a], Filippo Carducci[a,b,c], Febo Cincotti[a], Claudio Del Percio[a], Giulia Sirello[a], Claudia Fracassi[b], Anna C. Nobre[d], Paolo Maria Rossini[b,c,e]

[a] Dipartimento di Fisiologia Umana e Farmacologia, Università La Sapienza, Rome, Italy
[b] IRCCS S Giovanni di Dio Fatebenefratelli, Brescia, Italy
[c] AFaR.-Dip. di Neuroscienze, S. Giovanni Calibita, Fatebenefratelli Isola Tiberina, Rome, Italy
[d] Department of Experimental Psychology, University of Oxford, Oxford, UK
[e] Neurologia, Università Campus Biomedico, Rome, Italy

## Abstract

In the present high-resolution electroencephalographic (EEG) study, event-related desynchronization/synchronization (ERD/ERS) of alpha rhythms was computed during an S1–S2 paradigm, in which a visual cue (S1) predicted a SHORT (600 ms) or LONG (1400 ms) foreperiod, preceding a visual go stimulus (S2) triggering right or left finger movement. Could orienting attention to a selective point in time influence the alpha rhythms as a function of the SHORT vs. LONG foreperiod? Stronger selective attentional modulations were predicted for the SHORT than LONG condition. EEG data from 54 channels were "depurated" from phase-locked visual evoked potentials and spatially enhanced by surface Laplacian estimation (i.e., final data analysis was conducted on 16 subjects having a sufficient number of artifact-free EEG single trials). Low-band alpha rhythms (about 6–10 Hz) were supposed to be related to anticipatory attentional processes, whereas high-band alpha rhythms (10–12 Hz) would indicate task-specific visuo-motor processes.

Compared to the LONG condition (foreperiod), the SHORT condition induced a quicker and stronger ERS at low-band alpha rhythm (about 6–8 Hz) over midline and bilateral prefrontal, sensorimotor, and posterior parietal areas. In contrast, the concomitant high-band alpha (about 10–12 Hz) ERD/ERS showed no significant difference between the two conditions. In conclusion, temporal attention for a sub-second delay (800 ms) did modulate low-band alpha rhythm over large regions of both cortical hemispheres.
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## 1. Introduction

"Temporal attention" can be defined as a process aimed at allocating brain resources on the predicted onset of an incoming event. Previous studies on temporal aspects have mainly concerned subjective time estimation [10,29,32, 44,48]. Typically, they used S1–S2 paradigms in which a warning stimulus (S1) provided information on the duration of the time interval (foreperiod) preceding an imperative stimulus (S2) triggering a motor response. It has been shown that reaction time improves as a function of the temporal certainty of the warning and imperative stimuli [10–12,48], possibly due to an increase of alertness/vigilance [33,42].

Cortical regions involved in tasks where estimation of time where requested showed involvement of prefrontal, posterior parietal, supplementary motor, and temporal cortices [14,15,18,28,34,36], which are also engaged by "spatial attention" tasks [31,47,49]. With respect to the "spatial

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* Corresponding author. Sezione di EEG ad Alta Risoluzione, Dipartimento di Fisiologia Umana e Farmacologia, Università degli Studi di Roma "La Sapienza", P.le Aldo Moro 5 00185 Rome, Italy. Tel.: +39-06-49910989; fax: +39-06-49910917.

E-mail address: claudio.babiloni@uniroma1.it (C. Babiloni).

attention", the "temporal attention" tasks could induce a stronger activation of left hemisphere [13], skilled for serial processes.

In a recent S1–S2 study [35], event-related potentials (ERPs) have modeled the spatiotemporal evolution of the cortical activation during "temporal attention" towards incoming events. A warning cue stimulus (S1) predicted with 80% of validity an imperative stimulus (S2) after 600 or 1400 ms. The results have shown that the reaction time was faster when the visual cues correctly predicted the S1–S2 interval, thus suggesting a key role of the "temporal attention" on the performance. Furthermore, slow negative potentials (contingent negative variation, CNV) increased between S1 and S2 stimuli and were faster in shape when the S1 stimulus predicted a short (600 ms) rather than long (1400 ms) foreperiod. This was explained as a faster increase of the attentional resources with the short compared to long foreperiod. However, it should be remarked that CNV could not disentangle attentional respect to concomitant task-specific visuomotor processes. Theoretically, this could be do by the analysis of event-related desynchronization/synchronization (ERD/ERS) of "idling" electroencephalographic (EEG) alpha rhythms (6–12 Hz). The alpha ERD (i.e., percentage reduction in power) is proportional to the cortical information processing, whereas the ERS reflects the "recovery" of the neuronal activity after that processing [40]. Noteworthy, the low-band alpha ERD (about 6–10 Hz) would reveal unspecific "alertness" and/or "expectancy" ([25], Klimesch et al. 1996). In parallel, the concomitant high-band alpha ERD (about 10–12 Hz) would depend on task-specific sensory, motor, and/or semantic processes [22,24].

Here, EEG data of the mentioned study [35] were re-analyzed in terms of the ERD/ERS of the alpha sub-bands, which are differently sensitive to concomitant attentional (low-band alpha) and task-specific visuo-motor (high-band alpha) processes. Could temporal attention modulate the alpha rhythms as a function of short vs. long foreperiod (i.e., just difference of 800 ms)? Throughout the foreperiod, stronger selective attentional modulation were expected for the short than long condition.

## 2. Methods

Full details on the experimental procedures were previously reported [35]. In the following, we just summarized them.

### 2.1. Subjects

Experiments were performed in 21 healthy, right-handed (Edinburgh Inventory) adult volunteers (age range 18–38 years, 14 females), who gave their informed written consent. Visual acuity was normal or corrected to normal.

### 2.2. Experimental task

The experimental paradigm is illustrated in Fig. 1. The experimental task used two centrally placed cues that enabled subjects to predict when a subsequent target would occur. Each cue consisted of a narrow or wide cross (with an upper angle of 30° or 60°, respectively) and was flashed for 100 ms inside a circle of 1.7° of visual angle (continuously present). The appearance of the narrow or wide cross did cue the subject to expect either a SHORT (600 ms) or a LONG (1400 ms) interval between cue onset and the appearance of the target. The designation of which cue corresponded to either a short or long interval was counterbalanced across subjects. The target consisted of the brightening of the circle surrounding the cue for 100 ms. Two possible intervals between cue and target occurred in an unpredictable sequence. The between trial onsets interval was randomized and ranged between 3000 and 4300 ms. Each subject performed 10 blocks of trials. The first two were practice blocks. Blocks consisted of 100 trials in total: 40 valid trials for each cue type (e.g., cue predicts long interval, target appears at 1400 ms); 10 invalid trials where the target occurred at the unpredicted time interval (namely, the cue predicts long interval, target appears at +600 ms); and 10 catch trials where no target occurred.

The subjects were informed, at the beginning of the experiment, about the relationship between cue type and target. They maintained visual fixation on a small cross that was present continuously at the center of the monitor. They were instructed to press a key with the index finger of the right or left hand as quickly as possible following onset of the target. Each subject used the left hand for half of the task and the right hand for the other half. The whole testing session lasted ~ 2 h, including short rest breaks after each block of trials. The subjects were instructed to suppress saccades and to avoid blinking during the task.

### 2.3. EEG recordings

EEG data were recorded in continuous mode (0.03–100 Hz bandpass; 250 Hz sampling frequency) with a 54-tin electrode cap. Electrodes were disposed according to the 10–20 International System. Electrooculogram were also collected. Electrooculogram monitored blinking or eye movements. Additional electrodes were used as ground and reference sites. The right mastoid served as the reference for all electrodes. Recordings obtained from a left mastoid electrode were used off-line to re-reference the scalp recordings to the average of the left and right mastoid.

### 2.4. Off-line preliminary data analysis

The EEG data were segmented in single trials each spanning from − 1000 ms to 1800 ms, the zerotime being the onset of the cue stimulus.
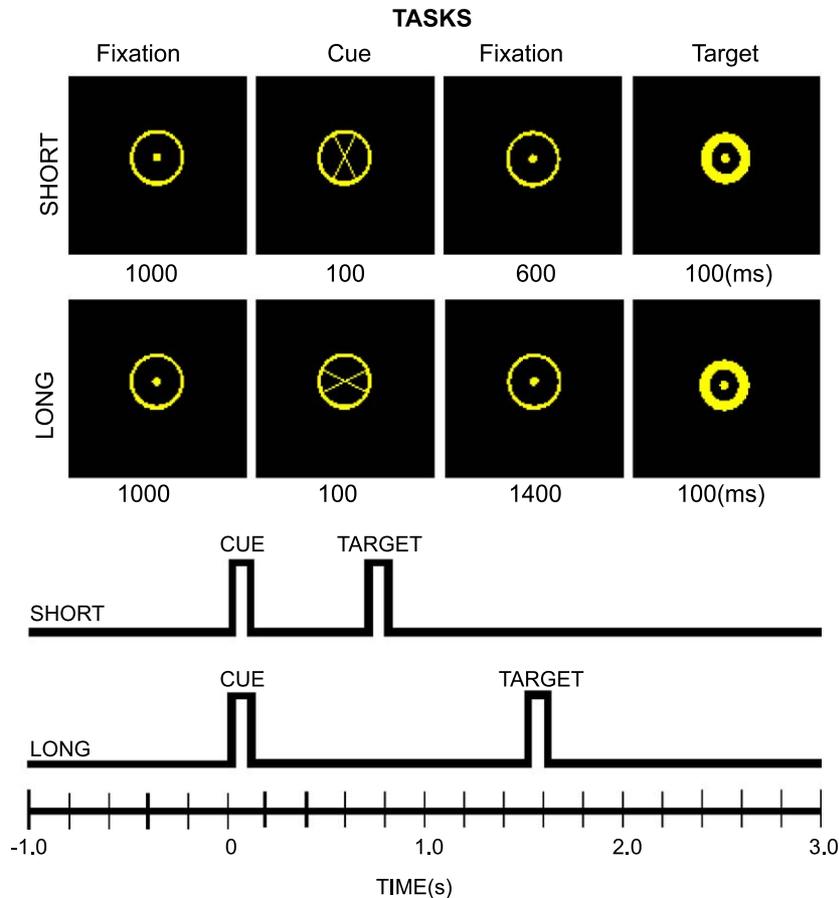
**TASKS**



Fig. 1. Task schematics for temporal orienting. Subjects maintained their gaze on a central fixation point. A brief cue (100 ms), either a narrow or wide cross, predicted the length of the interval between cue onset and the appearance of the target (600 or 1400 ms). The target was the brief brightening (100 ms) of the circle surrounding the cue. Subjects had to press a key with the index finger of the right or left hand as quickly as possible.

The EEG single trials contaminated by inadvertent motor acts, instrumental artifacts were discarded.

Spatial resolution of artifact-free EEG data was enhanced by surface Laplacian estimation (regularized 3-D spline function). The surface Laplacian estimation acts as a spatial filter that reduces head volume conductor effects and annuls electrode reference influence [2,38]. In some cases, the Laplacian values at the border electrodes were zeroed because of unreliability of the spline Laplacian estimate for these electrodes. Further details on the ''lambda'' regularization of the spline surface Laplacian estimate have been previously reported [2,3].

The single trial analysis was carefully repeated on the Laplacian-transformed EEG data, to discard the single trials contaminated by residual computational artifacts. In 5 out of 21 subjects, the number of artifact-free EEG single trials was lower than 15% of the individual data set. Consequently, they were excluded from final data analysis.

In the present study, we preliminary eliminated visual evoked potentials from background alpha EEG data. Evoked potential activity for each channel was obtained by averaging the bandpass-filtered Laplacian data EEG over all the trials. Then, a correction factor was calculated for each single trial by cross-correlation between average of evoked potential activity and the same EEG single trial. Finally, average of evoked potential activity for each channel, corrected by specific trial factor was subtracted from bandpass filtered Laplacian EEG data. A similar technique was successfully used in previous studies [26].

The artifact-free EEG trials (''depurated'' by evoked potentials) were subdivided into two groups, corresponding to the two different conditions. Namely, the SHORT group was for the trials presenting short cue-target period (600 ms) and the LONG group was for the trials presenting long cue-target period (1400 ms).

The artifact-free EEG valid trials (''depurated'' by evoked potentials) were subdivided into two groups, corresponding to the two different conditions (of note, the number of the artifact-free EEG invalid and catch trials was too low to be used for ERD/ERS data analysis). Namely, the SHORT group was for the trials presenting short cue-target period (600 ms) and the LONG group was for the trials presenting long cue-target period (1400 ms). The mean of individual artifact-free valid EEG data was of 209 single trials ($\pm$ 12 standard error, S.E.) for the SHORT condition and of 202 single trials ($\pm$ 17 S.E.) for the LONG condition. There was

no inter-condition statistical difference of the selected single trials as computed by a repeated measures ANOVA analysis ($F(1,15) = 2.7154$; MSe = 134; $p > 0.12$).

## 2.5. Determination of peak of individual alpha frequency (IAF)

The power spectrum analysis was based on a standard FFT approach using Welch technique and Hanning windowing function. For the determination of the individual alpha sub-bands, an anchor frequency was selected according to literature guidelines; the anchor frequency was the so-called IAF peak [21,23,25]. Practically, the IAF was defined as the frequency showing the higher power density in the 6–12 Hz spectrum. With reference to the IAF (Fig. 2), the frequency bands of interest were as follows: alpha 1 as IAF-4 Hz to IAF-2 Hz, alpha 2 as IAF-2 Hz to IAF and alpha 3 as IAF to IAF + 2 Hz. Table 1 reports the IAF for each subjects (i.e., in all subjects the IAF was the same for both SHORT and LONG condition). As a result, the mean ( ± S.E.) peak of the IAF was 9.3 Hz ( ± 0.2).

## 2.6. ERD/ERS computation

The ERD/ERS data were computed for alpha 1, alpha 2 and alpha 3 bands, based on the individual determination of the IAF. EEG time series were bandpassed (Bartlett function), squared, averaged across 120-ms periods (to 8 samples/s), and averaged across all single trials. The ERD/ERS

Table 1
IAF peak for each subject

| Subject no. | IAF |
|---|---|
| 1 | 10 |
| 2 | 10 |
| 3 | 10 |
| 4 | 10 |
| 5 | 10 |
| 6 | 10 |
| 7 | 10 |
| 8 | 8 |
| 9 | 10 |
| 10 | 8 |
| 11 | 10 |
| 12 | 8 |
| 13 | 8 |
| 14 | 8 |
| 15 | 10 |
| 16 | 10 |
| Mean | 9.3 |
| S.E. | ± 0.2 |

The IAF was defined as the frequency showing the higher power density in the 6–12 Hz spectrum. The IAF was the same for the SHORT and LONG condition in all subjects.

was defined as a percentage decrease/increase of instant power density at the "event" compared to a "pre-event" baseline (from − 500 ms to the zerotime; zerotime being onset of cue). Procedural details on ERD/ERS computation have been previously reported [39,41].

Individual ERD/ERS data sets were then interpolated by a spline function [1], in order to obtain ERD/ERS data sets at theoretical 54 electrode sites of augmented 10–20 system. These electrodes were disposed over a 3-D "quasi-realistic" head model (i.e., approximating each "realistic" individual head model). The template model was constructed based on the magnetic resonance data of 152 subjects, digitized at Brain Imaging Center of the Montreal Neurological Institute (SPM96).

## 2.7. Measurement of ERD/ERS latency and amplitude

For the alpha 1, alpha 2 and alpha 3 band, three fixed latencies T1, T2 and T3, respectively, at 200, 400 and 600 ms with respect to the zerotime, were computed. For the topographic mapping, the amplitude of ERD/ERS peaks (T1, T2, T3) was automatically measured for each experimental condition at each of the 54 electrodes. Across-subject means were then performed using these individual measured potential distributions.

## 2.8. Statistical analysis for SHORT and LONG conditions

Statistical comparisons for the SHORT and LONG conditions were performed by ANOVA analysis for repeated measures. Mauchley's test evaluated the sphericity assumption. Correction of the degrees of freedom was made by Greenhouse–Geisser procedure. Duncan test was used for post hoc comparisons ($p < 0.05$).
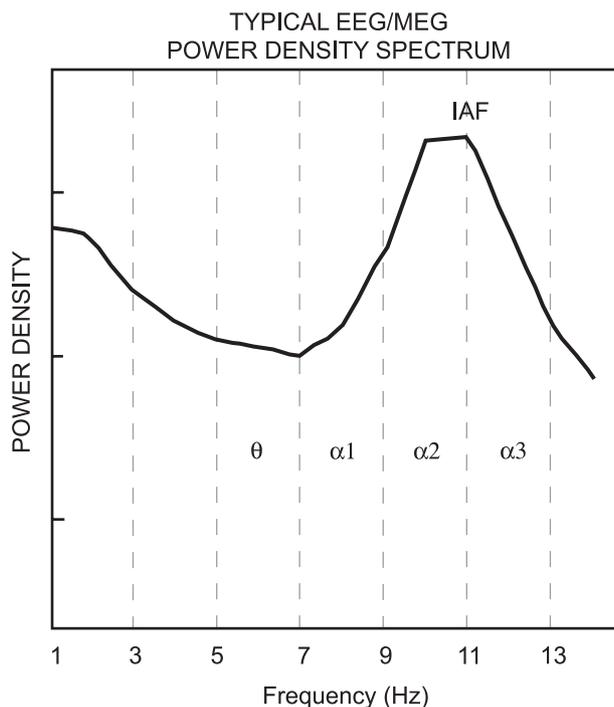


Fig. 2. Typical frequency spectrum computed from EEG data. Frequency bands of interest were alpha 1, alpha 2 and alpha 3, which were computed according to a well-known procedure based on the detection of IAF peak on such a spectrum (see Methods for further explanations).

The statistical analysis was performed at selected EEG electrodes representing cortical regions of interest (ROIs) for visuomotor transformations and attentional processes, i.e., prefrontal left (FL or F3 site), prefrontal right (FR or F4 site), central left (CL or C3 site), central right (CR or C4 site), posterior parietal left (PL or P3 site), and posterior parietal right (PR or P4 site). In addition, selected electrodes overlying cortical midline (Fz, Cz, and Pz sites) were considered for the evaluation of cortical activity of attentional cingulated areas.

A first ANOVA analysis was designed for the study of hemispherical representation of the temporal attention included the following factors (levels): Condition (SHORT, LONG), Band (alpha 1, alpha 2, alpha 3), Region of interest (F3, F4, C3, C4, P3, P4), and Time (T1, T2, T3). The prediction was for a statistical interaction including the Factor Condition and Band, indicating quicker attentional (low-band alpha 1 and/or alpha 2) effects for the SHORT than LONG condition.

A second ANOVA analysis was designed for the study of midline representation of the temporal attention included the following Factors (levels): Condition (SHORT, LONG), Band (alpha 1, alpha 2, alpha 3), Region of interest (Fz, Cz, Pz sites), and Time (T1, T2, T3). The prediction was the same as for the previous ANOVA design.

## 3. Results

### 3.1. Spatio-temporal distribution of ERD/ERS peaks

Fig. 3 illustrates the topographical maps of alpha ERD/ERS at fixed latencies such as T1 ($+200$ ms), T2 ($+400$ ms), and T3 ($+600$ ms) for SHORT and LONG conditions (grand average). For the SHORT condition, a largely diffused alpha ERD was observed at T1. Afterwards (T2 and T3), amplitude of the ERD values reduced especially at alpha 1 band. Notably, a sustained ERD was seen over left central area (C3) at alpha 3 band. Compared to the SHORT condition, the LONG condition was characterized by a weaker ERS at alpha 1 band.

### 3.2. Statistical analysis of alpha ERD/ERS

The ANOVA analysis for the evaluation of the hemispherical representation of alpha ERD/ERS showed a statistical interaction ($F(4,60) = 5.25$; MSe $= 205.7$; $p = 0.011$) among the factors Condition (SHORT, LONG), Band (alpha 1, alpha 2, alpha 3), and Time (T1, T2, T3). Fig. 4 (top) illustrates the means ($\pm$ S.E.) of the ERD/ERS representing the results of this ANOVA interaction. Duncan post hoc testing indicated that, at alpha 1, ERS peak was stronger for SHORT than LONG condition at T3 ($p < 0.00052$), independently by the regions of interest. On the whole, these results support the hypothesis of different spatio-temporal alpha 1 ERD/ERS (as an index of attentional processes) during the SHORT, with respect to the LONG, condition.

The ANOVA analysis above also showed a statistical interaction ($F(20,300) = 5.725$; Mse $= 156$; $p < 0.00001$) among Band (alpha 1, alpha 2, alpha 3), Region of interest (F3, F4, C3, C4, P3, P4), and Time (T1, T2, T3). Fig. 4 (bottom) illustrates the means ($\pm$ S.E.) of the ERD/ERS representing the results of this ANOVA interaction. Duncan post hoc testing indicated that, at alpha 1, ERS peak was stronger for SHORT than LONG condition at T3 ($p < 0.00052$), independently by the regions of interest. In contrast, alpha 3 was characterized by a sustained central ERD peak across T1, T2 and T3.
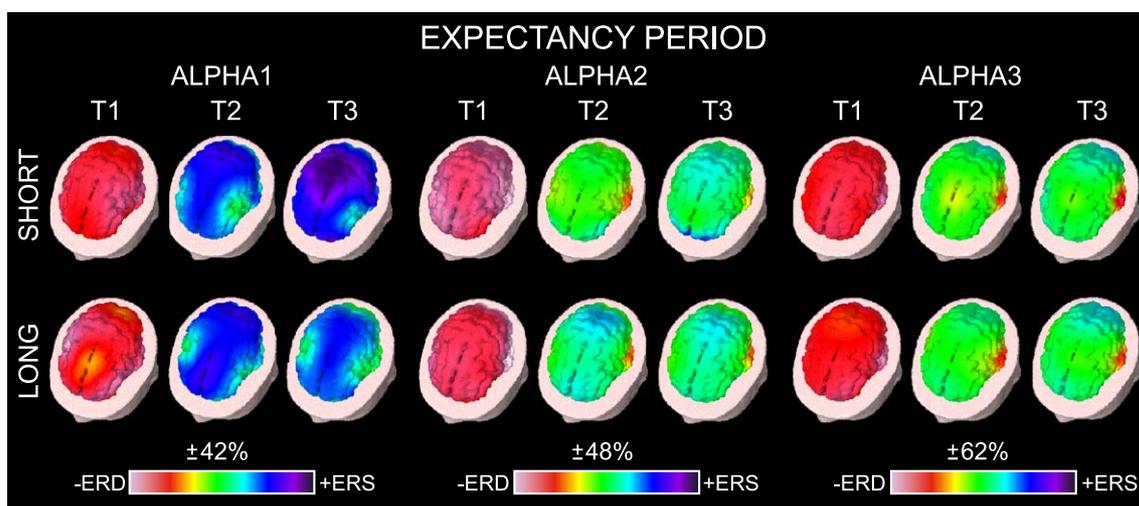


Fig. 3. Three-dimensional color maps of across-subject alpha 1, alpha 2 and alpha 3 at the ERD/ERS distributions, for the SHORT and LONG conditions. The maps refer to three fixed latencies at $+200$ ms (T1), $+400$ ms (T2), and $+600$ ms (T3) with respect to the zerotime (onset of the warning stimulus) within the period preceding the imperative stimulus. The amplitude of the ERD/ERS (T1, T2, T3) was automatically measured for each experimental condition at each of the 54 electrodes. Across-subject means were then performed using these individual measured potential distributions. Color scale: maximum ERD and ERS values are coded in white and violet, respectively. The values of ERD/ERS peaks are reported under the corresponding maps.
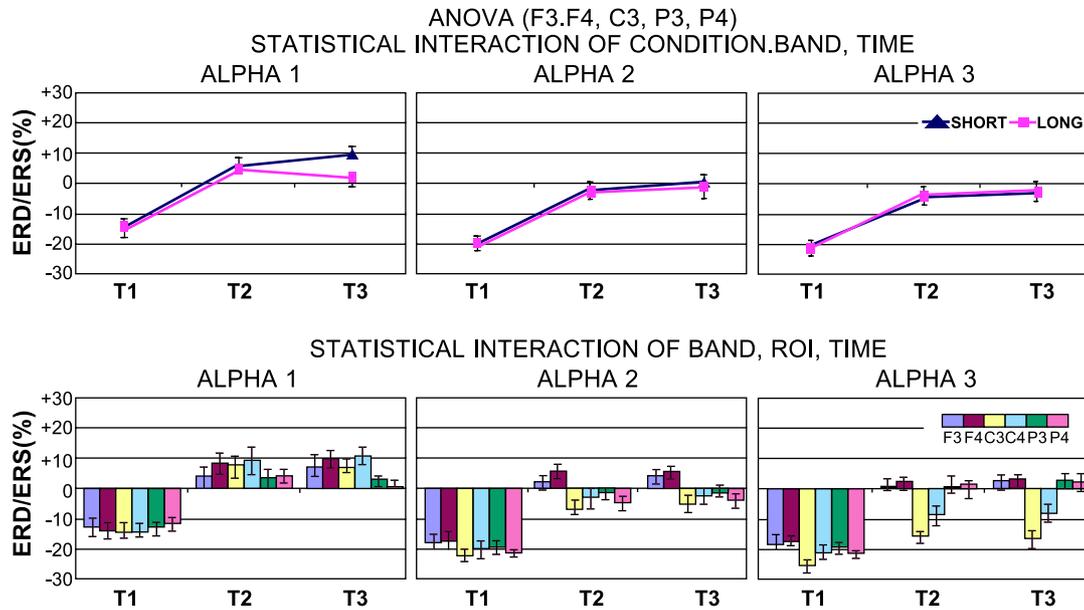
ANOVA (F3.F4, C3, P3, P4)
STATISTICAL INTERACTION OF CONDITION.BAND, TIME



Fig. 4. Across subject means ( ± S.E.) of the ERD/ERS amplitudes as provided by the ANOVA design. In particular, these means refer to a statistical interaction among the factors Condition (SHORT, LONG), Band (alpha 1, alpha 2, alpha 3), and Time (T1, T2, T3) (top figure side), and to a statistical interaction among the factors Band (alpha 1, alpha 2, alpha 3), Region of interest (FL, FR, CL, CR, PL, PR), and Time (T1, T2, T3) (bottom figure side). Legend: FL, F3 site (10–20 International System); FR, F4 site; CL, C3 site; CR, C4 site; PL, P3 site; PR, P4 site.

The ANOVA analysis for the evaluation of the midline alpha ERD/ERS showed a statistical interaction ($F(4,60) = 3.73$; MSe = 155.9; $p = 0.0089$) among the factors Condition (SHORT, LONG), Band (alpha 1, alpha 2, alpha 3), and Time (T1, T2, T3). Fig. 5 illustrates the means ( ± S.E.) of the ERD/ERS representing the results of this ANOVA interaction. Duncan post hoc testing provided results similar to those of first ANOVA analysis.

### 3.3. Control analyses

The interesting evidence of a stronger alpha 1 ERS at +600 after the warning stimulus for the SHORT than LONG conditions raised the issue of a comparison of the alpha 1 ERD/ERS at corresponding instants with respect to the go (target) stimulus. Therefore, the alpha 1 ERS was compared at 100 ms before the go (target) stimulus, namely +600 and +1400 ms after the warning stimulus for the SHORT and LONG conditions, respectively. The ANOVA

analysis included the factors Condition (SHORT, LONG) and Region of interest (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4). There was no statistical effect, indicating that the amplitude of the alpha 1 ERS was similar over the whole scalp before the go (target) stimulus.

The above results raised the issue of the effects of the motor preparation processes on the lateralization of the alpha ERD. To address this issue, the alpha ERD/ERS for the right and left finger movements were compared. For the SHORT condition, the mean of the RIGHT and LEFT single trials was 106 ( ± 6 S.E.) and 103 ( ± 8 S.E.), respectively. Analogously, the mean of the RIGHT and LEFT single trials for the LONG condition was 102 ( ± 6 S.E.) and 100 ( ± 6 S.E.), respectively. Of note, there was no statistical difference (ANOVA; $p > 0.4$) in the number of the selected single trials.

The ANOVA analysis for the alpha 1, alpha 2 and alpha 3 ERD/ERS included the factors Condition (SHORT, LONG), Side of movement (RIGHT and LEFT), Region of interest
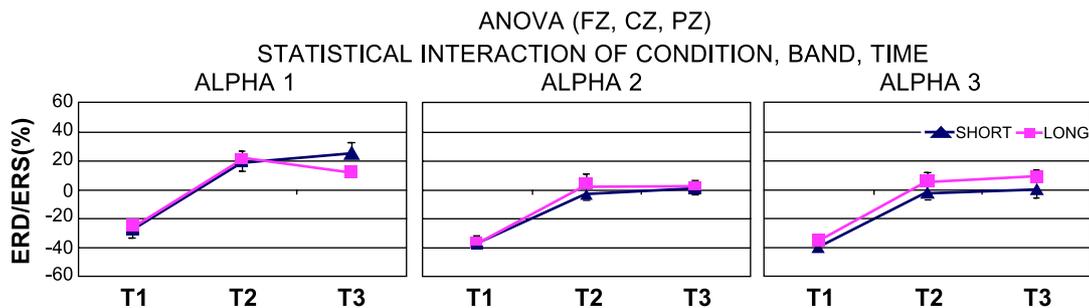
ANOVA (FZ, CZ, PZ)
STATISTICAL INTERACTION OF CONDITION, BAND, TIME



Fig. 5. Across subject means ( ± S.E.) of the ERD/ERS amplitudes as provided by the ANOVA design. In particular, these means refer to a statistical interaction among the factors Condition (SHORT, LONG), Band (alpha 1, alpha 2, alpha 3), and Time (T1, T2, T3).
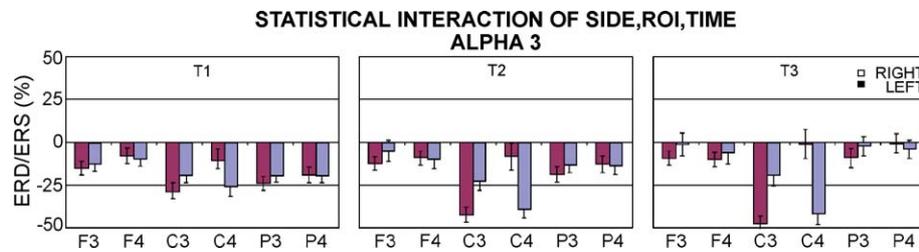
Fig. 6. Across subject means ( ± S.E.) of the alpha 3 ERD/ERS amplitudes illustrating the results of the ANOVA design having factors Condition (SHORT, LONG), Side of Movement (RIGHT and LEFT), Region of interest (F3, F4, C3, C4, P3, P4), and Time (T1, T2, T3). In particular, these means refer to a statistical interaction among the factors Side of Movement, Region of interest, and Time.

(F3, F4, C3, C4, P3, P4), and Time (T1, T2, T3). The results for the alpha 1 and alpha 2 showed nor significant main effect neither statistical interaction including Condition and/ or Side of movement as factors ($p > 0.5$). Instead, the results for the alpha 3 pointed to a statistical interaction ($F = 2.76$, $p < 0.004$) among the factors Side of movement, Region of interest, and Time. Fig. 6 illustrates the means ( ± S.E.) of

the alpha 3 ERD/ERS representing this ANOVA interaction. Duncan post hoc testing confirmed a statistically significant ($p < 0.005$ to $0.000004$) increment of the alpha 3 ERD at the central locations contralateral to the left (C4) and right (C3) movements, when compared to the ipsilateral locations. These differences increased across T1, T2 and T3 indicating that the motor processes mainly affected the lateralization of the central alpha 3 ERD. The topographic mapping of the alpha 3 ERD is illustrated in Fig. 7. It is noted the increase of the alpha ERD in the central areas contralateral to the movements and that the alpha 3 ERD in the ipsilateral central area is slightly more pronounced before the left than right movements.

## 4. Discussion

### 4.1. Methodological remarks

In the present study, EEG data were spatially enhanced by the surface Laplacian estimation, which minimized potentials originated from sub-cortical sources and removed the effects of reference electrode [38]. However, the present surface Laplacian estimates should be interpreted with caution. Surface Laplacian maxima could not overlie cortical sources of EEG potentials, due to the influence of tangentially oriented cortical generators [1,2]. As a consequence of the intrinsic limitations in spatial resolution, we investigated attentional effects as revealed by alpha ERD/ERS over large cortical regions of interest such as prefrontal (frontal), sensorimotor (central), and posterior parietal (parietal) areas of the two hemispheres. In addition, cortical midline was considered. This choice minimized the localization errors, so that our conclusions can be considered as reliable at that spatial scale. A more precise source analysis might have been obtained by dipole localization or linear inverse estimation of EEG data [6]. However, we anchored to a simple mapping of surface Laplacian ERD/ERS that has provided very interesting findings on human cortical responses to somatosensory and motor demands [4,5,7,8]. This approach avoided any kind of computational assumptions at an early stage of research (i.e., number of dipoles, regularization parameters of the linear inverse estimation, etc).
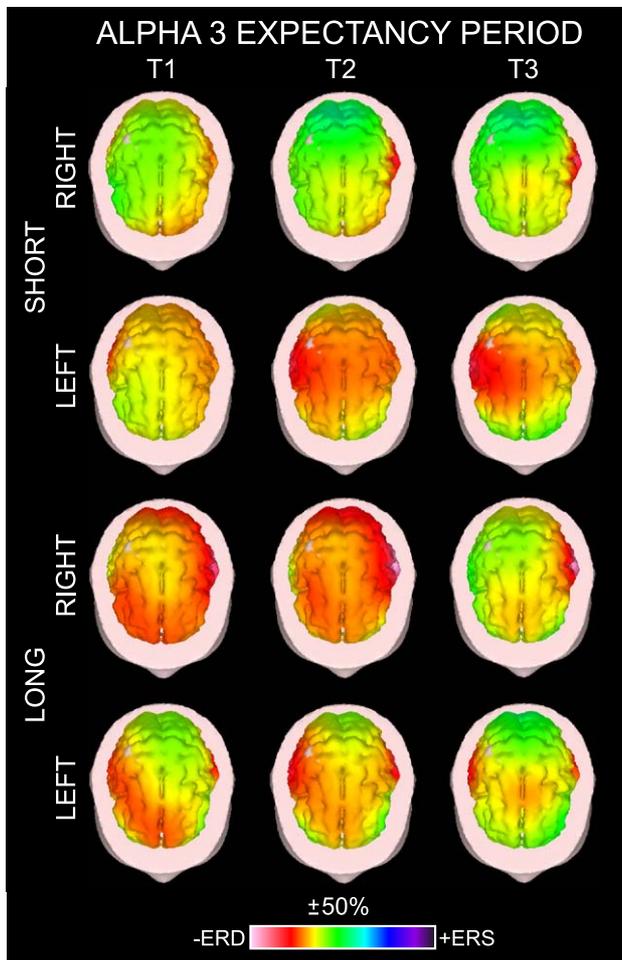


Fig. 7. Three-dimensional color maps of the alpha 3 ERD/ERS before the RIGHT and LEFT finger movements for the SHORT and LONG conditions. The maps refer to +200 ms (T1), +400 ms (T2), and +600 ms (T3) with respect to the onset of the warning stimulus. Color scale: maximum ERD and ERS values are coded in white and violet, respectively. The maximal (%) value of the ERD/ERS is reported.

Here, the determination of the individual alpha sub-bands followed the influential guidelines by Klimesch's group [21,23,25]. That approach has provided a body of evidence that the analysis of individual EEG frequency bands can disclose invaluable information on brain rhythmicity beyond standard definition of alpha at 8–12 Hz [23,27,37]. In particular, Klimesch's group has demonstrated that, with respect to the standard frequency bands, the individual frequency bands were able to disentangle the different behaviour of theta and alpha bands during cognitive demands, namely the theta ERS coupled with the alpha ERD [21,23].

### 4.2. Rapid changes (i.e., Within 600 ms) of "temporal attention" as revealed by low-band alpha ERD/ERS

In the present study, the amplitude of low-band alpha ERD (alpha 1) peaked with comparable values during SHORT and LONG foreperiod (i.e., between S1 and S2 stimuli). On the contrary, the following ERS values were greater in magnitude during the SHORT compared to LONG foreperiod. As expected, modulation of attention during a temporal intervals was faster and stronger with the SHORT than with the LONG condition, as a consequence of the fact that the go stimulus (S2) was expected earlier, indicating a specific ability to optimize performance relatively to the type of information available (i.e., time). Remarkably, the effect was band-specific, namely it was observed at alpha 1 but not alpha 2 and 3. These results agree with previous evidence of a time modulation of alpha 1 ERD/ERS as a function of the foreperiod length [23].

From a physiological point of view, the present alpha 1 ERS might be considered as a "recovery" of the neuronal activity after the warning stimulus and once the expected target time is very close to be delivered [40]. However, it should be made clear that it is not possible here to explain the alpha recovery in terms of active inhibition or removal of excitatory drive associated with GABA-ergic and gluta-mate-ergic processes, respectively. This issue should be addressed by future studies combining EEG data with those of paired transcranial magnetic stimulations according to a previous fruitful methodological approach [16,17,30,43,45].

The alpha 1 ERS raised two issues. Was the alpha 1 ERS before the go (target) stimulus affected by motor preparation and was it stronger for the SHORT than LONG conditions? To address these issues, the alpha 1 ERS was compared at 100 ms before the go (target) stimulus, namely +600 ms and +1400 ms after the warning stimulus for the SHORT and LONG conditions, respectively. The results showed no statistical difference at any scalp site of interest. They corroborated the idea that alpha 1 ERS reflected "temporal attentional" rather than motor processes, given that no alpha 1 ERD was observed before the go (target stimulus) and no effect was specific for the central electrodes overlying the sensorimotor areas. On the other hand, the results indicated that, in the two conditions, the "temporal attention" was equally engaged before the go (target) stimulus. On the whole, the present results suggest that the "temporal attention" was modulated before in the SHORT than LONG conditions, but its absolute magnitude was similar before the go (target) stimulus.

In the present study, the modulation of low-band alpha ERD/ERS during the foreperiod was distributed over a large neural network including prefrontal, premotor/primary sensorimotor, and posterior parietal cortical areas of both hemispheres as well as frontoparietal midline. Such a large distribution of the low-band alpha ERD/ERS is compatible with the attentional processes impinging upon wide visual, sensorimotor, and associative cortical areas. This is a further evidence that the low-band alpha ERD presents the widespread spatial features typical of the neural correlates of "alertness" processes [23]. Notably, the modulation of attention over time in the present experimental conditions did not prevail on the left hemisphere as expected based on its abilities for sequential information processing.

For both SHORT and LONG conditions, the task-specific visuomotor processes as revealed by alpha 3 ERD were prolonged over premotor/primary sensorimotor areas during the late phase of the foreperiod. The effects were located over the hand sensorimotor cortex, which prepared the motor response before the go stimulus. The lack of differences between the SHORT and LONG conditions was reasonably due to the similar length of the foreperiod periods, namely 600 ms for SHORT condition and 1400 ms for the LONG condition. A difference of only 800 ms could not dissociate the preparation of the movement in the two conditions as revealed by high-band alpha ERD/ERS, in contrast to what revealed by low-band alpha ERD/ERS. The use of a longer foreperiod (i.e., cue-target) interval might have dissociated the task-specific visuomotor processes associated with the movement preparation. However, the use of a third condition with a longer foreperiod interval would have lengthened the whole experimental session in excess. A long experimental session could have increased the level of fatigue and distraction, thus contaminating the experimental results. On the other hand, an increase of the interval would have give enough time to the subject to reorient his attention congruently to the information build during invalid cues, while we wanted to stress difference between expectations and the ability do direct attention at precise time points at different intervals, as well as the ability to direct attention in a punctuate mode congruent to the information given by the cue even during very short time intervals. Nevertheless, in this very task "temporal orienting" was probably tuned at motor response level as request by instructions. Any task is strictly relate to the nature of the information available, and in this case the low number of variable for a correct response was univocally related to a specific motor requirement at a time point and not to a visual perception level.

A prolonged and strong alpha 3 ERD over bilateral central areas raised the issue of the effects of the motor

preparation processes on the lateralization of the alpha 3 ERD. To address this issue, the alpha ERD/ERS for the right and left finger movements were separately considered and compared. The alpha 3 ERD was stronger in the contralateral than ipsilateral central areas and increased across the foreperiod preceding the imperative stimulus. These results suggest that the central alpha 3 ERD was selectively affected by the motor processes related to the hand to be moved, regardless the SHORT or LONG condition. This explanation is also corroborated by a preponderant left (dominant hemisphere) central alpha 3 ERD before ipsilateral movements compared to the right (non-dominant hemisphere) central alpha 3 ERD before ipsilateral movements, in line with previous EEG and functional magnetic resonance evidence [9,19,20,46].

The present alpha ERD/ERS results complement the original evaluation of the ERPs from the same database [35]. That evaluation had suggested stronger attentional processes during the SHORT than LONG conditions (i.e., quicker reaction time data), as revealed by a quicker reaction time together with an increment of the centro-parietal midline CNV amplitude. Here, that explanation was corroborated and enlightened by a stronger low-band alpha ERS during the SHORT than LONG conditions. This result occurred over a large cortical region spanning frontal, central, and parietal areas, thus pointing to an implication of alpha rhythmicity to enhance general "alertness" in associative and visuo-motor cortical systems ([25], Klimesch et al. 1996). On the whole, the combination of the ERPs and alpha rhythmicity provided a more complete view of the underlying cortical processes, beyond the idea of a unique pattern of event-related "cortical activation/deactivation". This motivates future field investigations on attentional processes using a multi-modal approach including ERPs, ERD/ERS, and behavioural measurements.

## 5. Conclusions

In this EEG study, the parallel "temporal attention" and task-specific visuo-motor processes, as revealed by alpha ERD/ERS, were modeled. The experimental task provided a cue stimulus predicting short or long foreperiod between the warning and imperative stimuli. The time difference between short and long foreperiods was of only 800 ms. Nevertheless, compared to the LONG condition, the SHORT condition induced a quicker and stronger ERS at the slowest alpha sub-band (about 6–8 Hz) over midline and bilateral prefrontal, sensorimotor, and posterior parietal areas. In contrast, the concomitant high-band alpha (about 10–12 Hz) ERD/ERS showed no significant difference in the two conditions. These results suggest that the "temporal attention" towards immediate future events, as revealed by the low-band alpha rhythm, was modulated over large regions of both cortical hemispheres at a time scale of less than 800 ms (time difference between SHORT and LONG

foreperiods). Remarkably, no functional asymmetry in favor of left phonological or right visuo-spatial hemisphere was found.

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